THE APPLICATION OF COMBINED MOMENTUM AND BLADE ELEMENT THEORY FOR AERODYNAMICS PERFORMANCE ANALYSIS OF ROTATING BLADES

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ABASTRACT

Computer code for performance aerodynamics analysis of three types of rotating blade configuration had been successfully developed. The computer code which developed based on the combined Momentum and Blade Element Theory can be applied for Horizontal axis wind turbine performance analysis, rotor blade helicopter in vertical climb and forward flight and the aircraft propeller analysis. The Combined Momentum and Blade Element Theory required the detailed blade geometry involves the chord and twist angle distribution along blade span and also the aerodynamics characteristics of its airfoil section. The developed computer code allows one to obtain the detail of differential thrust coefficient, differential torque coefficient and differential power coefficient along blade span. Integrate those differential quantities will give the thrust coefficient, torque and power coefficients. The comparison result with other method or experimental result were not yet be done due to difficulties in obtaining suitable data for such purposes. Hence the comparison result with other method has been suggested for the future work.

ABSTRAK

Komputer kod untuk analisis prestasi aerodinamik untuk tiga jenis konfigurasi bilah yang berputar telah berjaya dibangunkan. Komputer kod yang dibangunkan adalah berdasarkan gabungan momentum dan teori element bilah yang boleh digunakan untuk prestasi turbin angin pada kedudukan menegak,bilah berputar bagi helikopter dalam kedudukan mendatar dan penerbangan maju dan analisis propeller pesawat. Gabungan momentum dan teori element bilah memerlukan geometri bilah secara terperinci yang melibatkan '*chord'* dan pengedaran '*twist*' sudut di sepanjang span bilah dan juga ciri-ciri aerodinamik pada bahagian Aerofoil. Komputer kod yang dibangunkan membolehkan kita untuk mendapatkan perincian daripada pekali pembezaan, pekali pembezaan kilas dan pekali kuasa pembezaan di sepanjang permukaan bilah. Mengintegrasikan jumlah pembezaan akan memberikan pekali, pembezaan, daya kilas dan pekali kuasa. Keputusan perbandingan dengan kaedah lain atau hasil eksperimen belum dilakukan kerana kesulitan dalam memperoleh data yang sesuai untuk tujuan tersebut. Maka hasil perbandingan dengan kaedah yang lain telah dicadangkan untuk kajian di masa hadapan.

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LIST OF MAIN SYMBOLS

a	axial interference or induction factor
a'	angular induction factor
A	airfoil area (chord × span), surface area, rotor swept area
A	axial (chord) force
C_d	drag coefficient
C_l	lift confficient
C_p	pressure confficient
C_P	rotor power coefficient
C_{P_i}	induced power confficient
C_Q	torque conefficient
C_T	thrust conefficient
c	blade chord, airfoil chord
r	rotor radius
$\dot{m}$	mass flow
t	time
D	diameter, drag, propeller diameter
k	index of blade element closest to hub

L	characteristic length, lift force
F	force
Q	torque
T	thrust
N	number of blade eleament
U	characteristic velocity, velocity of undisturbed airflow
V	velocity of advance
L	characteristic length, lift force
J	propeller advance ratio
x	dummy varible
α	angle of attack
β	blade engle
ε	axial kinetic egergy factor
λ	advance ratio
λ_h	local speed ratio at the hub
λ_r	local speed ratio
λ_c	climb inflow ratio
λ_i	rotor induced inflow ratio
ρ	density of air
σ	solidity
ω	the angular velocity
θ	angular coordinate in the sestem masstransport coefficient
Ω	anguler velocity of rotor, angular velocity about spin axis

η	efficiency (electrical, meckanical) (%)
η_i	ideal efficiency
ψ	azimuh angle around a rotor, stresm function
d_r	thickness
μ	coefficient of friction, dimensionless airplan mass
γ	ratio of specific angle
φ	phase angle
ν	kinematic air viscosity
B	number of blade

Subscripts and superscripts

i	induced
∞	free stream flow condition
l	lower surface
0	reservoir conditions
0	sea level
0	midspan
w	Used as index for normal rotor average normal induction

Abbreviations

AC	alternating current
BEM	blade element theory
HAWT	horizontal axis wind turbine
rpm	rotations per minute
VAWT	vertical axis wind turbine

CHAPTER1

THE APPLICATION OF COMBINED MOMENTUM AND BLADE ELEMENT THEORY FOR AERODYNAMICS PERFORMANCE ANALYSIS OF ROTATING BLADES

1.1 Introduction

The rotating blade applications had been found in many engineering applications. This type of devices had been used for generating thrust such as for the propeller aircraft, , rotor blade helicopter and they may for extracting the kinetic energy of the airflow such as on the horizontal axis wind turbine. There are various method can be used to estimate the performance of such devices, they are namely : the Momentum Theory, Blade Element theory, the Combined Momentum-Blade Element Theory, a Prescribed wake Method, a Free Wake Method or The Method which derived from solving the governing equation of fluid motion such as a Three Dimensional Euler Equation or Three Dimensional Time Averaged Navier Stokes equation.

The simple momentum theory provides an initial idea regarding the performance of a propeller but not sufficient information for the detailed design. Detailed information can be obtained through analysis of the forces acting on a blade element like it is a wing section. The forces acting on a small section of the blade are determined and then integrated over the propeller radius in order to predict the thrust, torque and power characteristics of the propeller.

The present work will explore the implementation of the idea of Combined Momentum – Blade Element Theory for predicting the aerodynamics performance for : propeller blade of the aircraft, rotor blade helicopter in hover and forward flight and also the rotor blade of the horizontal axis wind turbine.

1.2 Research Background

There are engineering applications used a rotating blade devices to carry out a particular tasks. Rotating blade on wind turbine is designed to convert the wind kinetic energy to become a useful energy such as for generating electricity or in the form of mechanical work for water pumping. Rotating blade on propeller aircraft is designed to generate thrust through converting the mechanical power to the kinetic energy of the airflow which pass through the blade. It is similar with what occured on the flow past through a rotor blade helicopter. Considering such importance of the rotating blade devices in generating thrust as well as in the way of extracting the wind kinetic energy in the problem of wind turbine, hence understanding performance for such devices are required. One will not be able to fly the airplane if the thrust generated by the propeller blade is not sufficient to overcome the aircraft drag. Similary the helicopter will also not be able to hover if the thrust at hover is less then the helicopter weight. Through these reasons, the research work was purposed to carry out on the development of computer code for performance rotating blade analysis.

1.3 Problem Statement.

The flow pass through rotating blade can be modelled by introducing a streamtube model in order to distunguish the flow surrounding the blade can be diveded into two regions disturbed and undisturbed flow region.

Here one can applied momentum conservation along the stream tube and in the same time one can formulate the forces which work on the blade in view of blade element theory. Those two approaches will give the same forces quantatively and equoting them makes the mathematical expression for solving the unknown induced velocity can be developed. Such approach is konwn as the Combined Momentum and Blade Element Theory. This approach can be applied whether the rotating blade in the form of horizontal axis wind turbine, propeller aircraft or rotor blade helicopter.

However due to geometry differences in their configurations, the implementation of the combined Momentum and Blade element theory give a slightly different mathematical experession in the way of estimating the induced velocity. Such difference need to be clarified in order to make better understanding in implenting the combined Momentum and blade element theory for the case of rotating blade problems.

1.4 Objective

To develop computer code for the aerodynamics analysis of rotating blade by using a Combined Momentum – Blade Element Theory which applicable for propeller aircraft, and rotor blade helicopter and rotor blade of the horizontal axis wind turbine

1.5 Scope of Study

1. Overview on the progress development in the aerodynamic performance predicting method of rotating blade.
2. Identity the typical rotor blade configuration if those devices designed as propeller for the aircraft, rotor blade of the helicopter and as rotor blade for the horizontal axis wind turbine.
3. Develop computer code for the rotor blade aerodynamic performance analysis based on the idea of combined Momentum – Blade Element Theory.
4. Comparison result between the developed computer code for several test case of rotating blade which available in literature.

CHAPTER 2

THE ROTATING BLADE CONFIGURATION

2.1 Overview Various Methods for solving for aerodynamics performance analysis of rotating blade

R. Lanzafame, M. Messina (2008) [1] Horizontal axis wind turbine working at maximum power coefficient continuously. The performance of a horizontal axis wind turbine continuously operating at its maximum power coefficient was evaluated by a calculation code based on Blade Element Momentum (BEM) theory. It was then evaluated for performance and Annual Energy Production (AEP) at a constant standard rotational velocity as well as at a variable velocity but at its maximum power coefficient. The mathematical code produced a power co-efficiency curve which showed that notwithstanding further increases in rotational velocity a constant maximum power value was reached even as wind velocity increased.
This means that as wind velocity varies there will always be a rotational velocity of the turbine which maximizes its coefficient. It would be sufficient therefore to formulate the law governing the variation in rotational velocity as it varied with wind velocity to arrive at a power coefficient that is always the same and its maximum.
This work produced a methodology which allows a horizontal axis wind turbine to work continuously at its maximum power coefficient. A wind turbine operating at constant rotational velocity has a maximum power coefficient for a given wind velocity which decreases as wind speed decreases.

C Siva,MSMurugan, and R Ganguli(2009)[2] Effect of uncertainty on helicopter performance predictions. The effect of uncertainties on performance predictions of a helicopter is studied in this article. The aeroelastic parameters such as the air density, blade profile drag coefficient, main rotor angular velocity, main rotor radius, and blade chord are considered as uncertain variables. The propagation of these uncertainties in the performance parameters such as thrust coefficient, figure of merit, induced velocity, and power required are studied using Monte Carlo simulation and the first-order reliability method. The Rankine–Froude momentum theory is used for performance prediction in hover, axial climb, and forward flight. The propagation of uncertainty causes large deviations from the baseline deterministic predictions, which undoubtedly affect both the achievable performance and the safety of the helicopter. The numerical results in this article provide useful bounds on helicopter power requirements. The structural and aerodynamic uncertainty effects on helicopter performance predictions are presented. The MCS is carried out with 100 000 samples of structural and aerodynamic variables with a COV ranging from 1 per cent to 5 per cent.

The power coefficient for the hover case shows a large scatter in their predictions with a COV of 8.33 per cent and extreme values ranging from −30 per cent to 45 per cent from the baseline deterministic value. The power required of an axial climb shows a COV of 2.87 per cent and has a scattering of −10 per cent to 15 per cent from the baseline deterministic prediction. The power required for forward flight at $\mu_f = 0.1$ has a COV of 3.94 per cent and a deviation of −15 per cent to 25 per cent from the baseline, whereas for forward flight at $\mu_f = 0.3$, the power required has a COV of 1.54 per cent and a deviation of −6 per cent to 10 per cent from the baseline. Although the absolute power required may differ in hover, axial climb, and forward flight, the uncertainty propagation has much more impact over the hover deterministic prediction with a large COV of 8.33 per cent. These numerical results provide useful bounds on helicopter power requirements for hover, axial climb, and forward flight. The outcome of this work clearly shows the need to incorporate randomness of structural and aerodynamic properties in the helicopter design and performance analysis. Understanding the influence of various uncertainties on the performance of a helicopter is certain to augment the design process, thereby bringing significant improvements in range, endurance, operational flexibility, and safety The results of this study will enhance confidence in the design process and will gradually pave the way for safer aerospace systems through inclusion of uncertainty analysis in computer simulations.

Sung Nam Jung(2004)[3] Aerodynamic performance prediction of a 30 kW counter-rotating wind turbine system. The aerodynamics performance prediction of a unique 30 kw counter-rotating (C/R) wind turbine system, which consists of the main rotor and auxiliary rotor, has been investigated by using the quasi-steady strip theory. The near wake behavior of the auxiliary rotor that is located upwind of the main rotor is taken into consideration in the performance analysis of the turbine system by using the wind tunnel test data obtained for scaled model rotor. The relative size and the optimum placement of the two rotors are investigated through use of the momentum theory combined with the experimental wake model. In addition, the performance prediction results along with the full-scale field test data obtained for C/R wind turbine system are compared with those of the conventional single rotor system and demonstrated the effectiveness of the current C/R turbine system.The aerodynamics performance analysis has been carried out for a 30 kW C/R wind turbine system by using the quasi-steady strip theory along with the experimental wake model obtained based on the wind tunnel test data. The relative size and the optimum placement of the auxiliary rotor and the main rotor in the C/R system were identified. Regarding the relative dimension of the two rotors, the size of the auxiliary rotor should be smaller than one-half of the main rotor diameter. It is also, found that the power output was significantly affected by the interval remained at around one-half of the auxiliary rotor diameter. The full-scale test data for the performance of the C/R wind turbine system were compared with the present prediction results. A fairly good correlation between the two results was obtained. Based on the prediction results as well as the field test experience, the current C/R system through to be quite effective in extracting energy from the wind. The maximum power coefficient reached as high as 0.5.

2.2 Configuration of Rotating Blades

As it has mentioned in the previous chapter, the present works will conduct aerodynamics performance on three types of rotating blade.

They are namely (1) rotating blades of the propeller aircraft (2) the rotating blades of helicopter and (3) the rotating blades of the horizontal axis wind turbine.

Each of those rotating blades worked at difference operation conditions, as result there are a configuration differences among of them. The following subchapters discuss the typical of configuration for each of rotating blade as mentioned above.

2.2.1 Rotating blade configuration of Propeller Aircraft

Thrust is the force that moves the aircraft through the air. Thrust is generated by the propulsion system of the aircraft. There are different types of propulsion systems in the way to develop thrust, although it usually generated through some application of Newton's Third Law. Propeller is one of the propulsion systems. The purpose of the propeller is to move the aircraft through the air. The propellers consist of two or more blades connected together by a hub. The hub serves to attach the blades to the engine shaft [4].

The blades are made in the shape of an airfoil like wing of an aircraft. When the engine rotates the propeller blades, the blades produce lift. This lift is called thrust-and moves the aircraft forward. Most aircraft have propellers that pull the aircraft through the air. These are called ct or propellers. Some aircraft have propellers that push the aircraft. These are called pusher propellers [4].

2.2.2 Description of propeller aircraft

This section will describe some parts of propeller aircraft, the propeller part are as shown in the Figure 2.1 [5]

- **Leading Edge**

Of the airfoil is the cutting edge that slices into the air. As the leading edge cuts the air, air flows over the blade face and the camber side. [5]

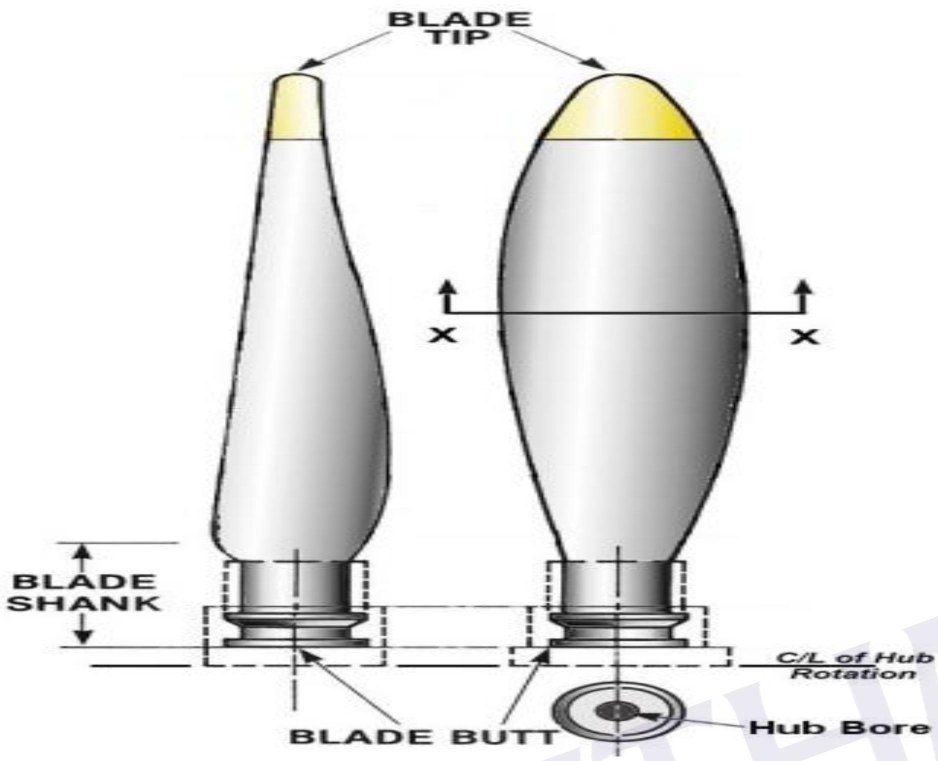

Figure 2.1 Leading Edge [5].

- **Blade face**

Is the surface of the propeller blade that corresponds to the lower surface of an airfoil or flat side, it called Blade Face.

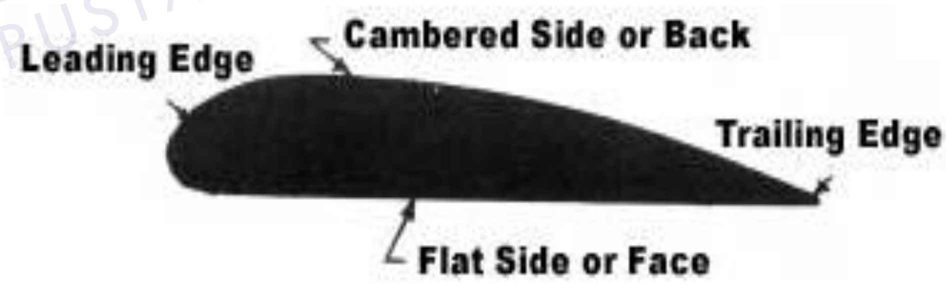

Figure 2.2 Cross section of a propeller blade [5]

- **Blade Back / Thrust Fac**e

Is the curved surface of the airfoil.

- **Blade Shank (Root)**

Is the section of the blade nearest the hub.

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